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Soil moisture estimation from Compact Polarimetry – a viable alternative for SMAP

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Abstract

In their 1995 paper, Dubois et al [1] showed how soil moisture can be estimated for vegetation-free areas from L-Band HH and VV radar backscatter measurements, acquired at an incidence angle of around 40 degrees, similar to SMAP. The algorithm also uses HV backscatter measurements to screen for vegetation-free areas using a simple threshold test. Implementation of this algorithm therefore requires three backscatter (intensity) measurements: HH, VV, and HV.

In this paper, we show how simple measurements of just two scattering components can be used in an adaptation of the Dubois et al algorithm to give remarkably consistent soil moisture estimates. The method involves the transmission of a circular polarization, and reception of two linear polarizations: H and V – a form of what is referred to as compact polarimetry. To efficiently screen for vegetation-free surfaces, we introduce a novel parameter known as the conformity coefficient, which allows the separation of areas for which surface, volume and double-bounce scattering mechanisms are dominant. This conformity coefficient is also invariant under Faraday rotation, which makes it quite robust. We also show how compact polarimetry signatures from vegetation-free surfaces can then be used to estimate (and correct for) Faraday rotation, a potentially critical error source. Finally, we show that soil moisture estimates derived from this approach are very similar (less than 2% relative difference) to those generated using the original Dubois et al algorithm.

In the context of SMAP, our new approach offers a simplified radar mode of operation (only two scattering measurements required instead of three or four); efficient separation of areas where surface, volume or double-bounce scattering is dominant; built-in estimation and correction of Faraday rotation; and the potential for the use of phase information, not just amplitude, especially where double-bounce scattering is dominant, e.g. from beneath forest canopies.

Dubois et al, 1995 algorithm:

$$\sigma^0_{HH} = 10^{-2.75}\frac{\cos^{1.5}\theta}{\sin^5\theta}10^{0.028\varepsilon\tan\theta}(kh\sin\theta)^{1.4}\lambda^{0.7} \quad (1)$$

$$\sigma^0_{VV} = 10^{-2.35}\frac{\cos^{3}\theta}{\sin^3\theta}10^{0.046\varepsilon\tan\theta}(kh\sin\theta)^{1.1}\lambda^{0.7} \quad (2)$$

$$\frac{\sigma^0_{HV}}{\sigma^0_{VV}} < -11 \text{ dB for bare surfaces.} \quad (3)$$

where θ is the incidence angle,
ε is the real part of the dielectric constant,
λ is the wavelength in cm,
kh is the electromagnetic roughness.

In the above, equations (1) and (2) describe empirically derived relationships between HH and VV backscatter measurements and soil dielectric and roughness properties. Equation (3) is used to screen the backscatter measurements for areas that are vegetation-free. The conversion from dielectric constant to volumetric soil moisture is performed using a set of empirical formulas [2] depending on the textural components of the soil.

Faraday Rotation

Including the effects of Faraday rotation, compact polarimetry measurements in the pi/2 mode [3] can be modeled as:

$$\begin{pmatrix} M_{RH} \\ M_{RV} \end{pmatrix} \cong \frac{1}{\sqrt{2}}e^{-j\Omega}\begin{pmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{pmatrix}\begin{pmatrix} S_{hh} & S_{vh} \\ S_{hv} & S_{vv} \end{pmatrix}\begin{pmatrix} 1 \\ -j \end{pmatrix} \quad (4)$$

Which expands to:

$$M_{RH} \cong S_{hh}\cos\Omega + S_{hv}(\sin\Omega - j\cos\Omega) - jS_{vv}\sin\Omega \quad (5)$$

$$M_{RV} \cong -S_{hh}\sin\Omega + S_{hv}(j\sin\Omega + \cos\Omega) - jS_{vv}\cos\Omega \quad (6)$$

Forming cross-products:

$$\langle M_{RH}M_{RH}^*\rangle \cong |S_{hh}|^2\cos^2\Omega + |S_{hv}|^2 + |S_{vv}|^2\sin^2\Omega + j2\,\mathrm{Im}(S_{hh}S_{vv}^*)\cos\Omega\sin\Omega \quad (7)$$

$$\langle M_{RV}M_{RV}^*\rangle \cong |S_{hh}|^2\sin^2\Omega + |S_{hv}|^2 + |S_{vv}|^2\cos^2\Omega - j2\,\mathrm{Im}(S_{hh}S_{vv}^*)\sin\Omega\cos\Omega \quad (8)$$

$$\langle M_{RH}M_{RH}^*\rangle + \langle M_{RV}M_{RV}^*\rangle \cong |S_{hh}|^2 + 2|S_{hv}|^2 + |S_{vv}|^2 \quad (9)$$

$$\langle M_{RH}M_{RV}^*\rangle \cong (|S_{vv}|^2 - |S_{hh}|^2)\cos\Omega\sin\Omega + jS_{hh}S_{vv}^*\cos^2\Omega - j|S_{hv}|^2 + jS_{vv}S_{hh}^*\sin^2\Omega \quad (10)$$

$$\mathrm{Re}\langle M_{RH}M_{RV}^*\rangle \cong (|S_{vv}|^2 - |S_{hh}|^2)\cos\Omega\sin\Omega - \mathrm{Im}(S_{hh}S_{vv}^*)(\cos^2\Omega - \sin^2\Omega)$$

$$\mathrm{Im}\langle M_{RH}M_{RV}^*\rangle \cong \mathrm{Re}(S_{hh}S_{vv}^*) - |S_{hv}|^2$$

And the FR angle can be estimated from signatures of surface scatterers (Fig. 1):

$$\Omega = \frac{1}{2}\arctan\left(2\frac{\mathrm{Re}\langle M_{RH}M_{RV}^*\rangle}{\langle M_{RV}M_{RV}^*\rangle - \langle M_{RH}M_{RH}^*\rangle}\right) \pm \frac{\pi}{4} \quad (11)$$

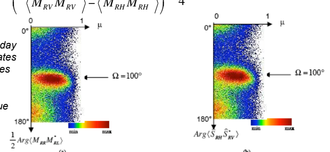


Figure 1: Faraday rotation estimates using signatures of surface scatterers. Simulated value of FR is 100º

What is Compact Polarimetry?

Conventional Polarimetry (linear basis)

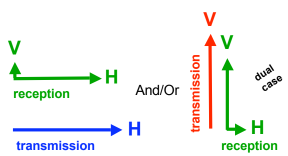


Figure 2. Illustration of conventional polarimetry, in which H and/or V linear polarization is used on transmit and both H and V polarizations are used on receive

Compact Polarimetry (pi/2 mode)

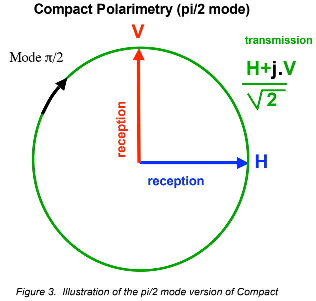


Figure 3. Illustration of the pi/2 mode version of Compact Polarimetry, in which circular polarization is used on transmit and both H and V polarizations are used on receive

The conventional approach to acquiring radar measurements with polarization diversity uses linear polarizations (Fig. 2). The simplest dual-polarized options include (HH, HV) and (VV, VH), which are acquired by transmitting either H or V polarizations, and receiving the return echo on both H and V channels.

Quad-pol mode usually involves alternating between H and V transmit, receiving both H and V for each, so that a set of (HH, HV, VH and VV) returns are collected. This is termed fully coherent quad-pol and the phase difference between measurements, particularly the HH compared with VV, carries information. Some systems employ a pesudo-quad-pol mode, in which H and V are transmitted on separate bandwidths or during different 'looks'. In pseudo-quad-pol mode the measurements are not coherent, and the phase difference between them does not carry useful information.
Compact or hybrid polarimetry ([4], [5]) is an attractive option for dual-polarized SAR (Fig. 3) that offers increased information content, as compared with conventional dual-polarized approaches (e.g. HH, HV). Compact polarimetry also offers the capability of measuring scattering from higher incidence angles and over larger swaths than conventional quad-pol data acquisition from space.

$$\text{Target Vector: } \vec{k} = \begin{bmatrix} S_{RH} \\ S_{RV} \end{bmatrix} \Rightarrow \begin{bmatrix} S_{HH} \pm jS_{HV} \\ S_{HV} \pm jS_{VV} \end{bmatrix}$$

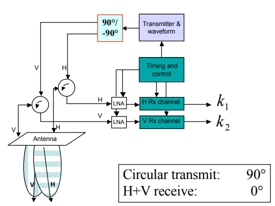


Figure 4. Block diagram representing a typical system architecture for the pi/2 mode CP (figure courtesy R. K. Raney, JHU/APL)

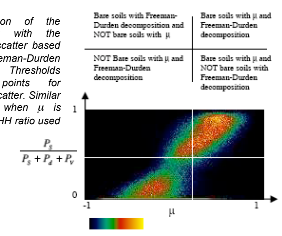
At longer wavelengths, which can be subject to significant Faraday rotation as they pass through the ionosphere, a circular polarization on transmission is the only approach that guarantees that the polarization incident on the ground is known. Transmission of any other elliptical or linear polarization does not have this property. If the system is then configured to receive linear (H, V) returns this π/2 mode can be shown to be, in many respects, the optimum dual-polarized configuration [3]. The scattering signatures from such a system, labeled (RH, RV) for the right-circular transmit case can then be corrected for (one-way) Faraday rotation on the return path. In addition, the receive polarization basis can be transformed to synthesize all possible combinations, e.g. (RR, RL).

Additional advantages of compact polarimetry are that it is relatively easy to implement (see Fig. 4), and the cross-product between the two measurements carries information even over natural terrain, particularly in the phase.

Conformity Coefficient

The conformity coefficient μ can be used as a discriminator between bare surface scattering, double bounce scattering and volume scattering:
- For surfaces, SHV is small, SHH and SVV are correlated and their phase is close to 0. As a consequence, μ is positive and conforms to 1: 1>μ>t1.
- For double-bounce scattering, SHH and SVV are correlated and their phase is close to 180°. μ is negative and conforms to: t2>μ>-1.
- For volume scattering, SHH and SVV are weakly correlated and SHV is large, μ has an intermediate value: t1>μ>t2.

Figure 6: Comparison of the conformity coefficient with the proportion of surface scatter based on the Freeman-Durden decomposition [6]. Thresholds indicate decision points for separation of surface scatter. Similar results are obtained when μ is compared with the HV/HH ratio used in Dubois et al. [1]



Soil Moisture estimation flow

Estimate FR invariant parameter (Eqs. 9, 10):

$$\mu = \frac{2\,\mathrm{Im}\langle M_{RH}M_{RV}^*\rangle}{\langle M_{RH}M_{RH}^*\rangle + \langle M_{RV}M_{RV}^*\rangle} \cong \frac{2\left[\mathrm{Re}(S_{hh}S_{vv}^*) - |S_{hv}|^2\right]}{\left(|S_{hh}|^2 + 2|S_{hv}|^2 + |S_{vv}|^2\right)}$$

↓

Apply a simple, threshold-based classifier:
1>μ>t_1 ==> Surface scatter
t_1>μ>t_2 ==> Volume scatter
μ< t_2 ==> Double-bounce

→ Fig. 7

↓

Find Ω from signatures of surface scatterers (Fig. 1) by maximizing

$$\mathrm{Re}\langle M_{RH}M_{RV}^*\rangle \approx (|S_{vv}|^2 - |S_{hh}|^2)\cos\Omega\sin\Omega > 0$$

↓

Correct for Ω

↓

Estimate soil moisture from bare soil surfaces using Dubois et al [1] algorithm (Figs. 7, 8)

Figure 5: Algorithm flow

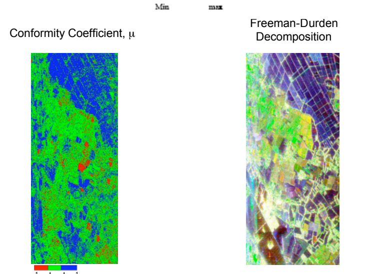


Figure 7: Classification based on the conformity coefficient compared with the Freeman-Durden decomposition, using simulated CP data derived from FP from the ONERA RAMSES system [7]

Surface Discrimination

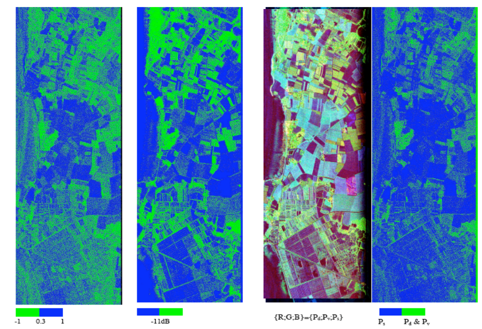


Figure 6: Comparison of surface scatter separation using the conformity coefficient, a HV/HH threshold, and the Freeman-Durden decomposition

Soil Moisture Estimation

- Results

Figure 7: Direct comparison of $|S_{RH}|^2$ with $|S_{HH}|^2$ and $|S_{RV}|^2$ with $|S_{RV}|^2$ for surface scatterers

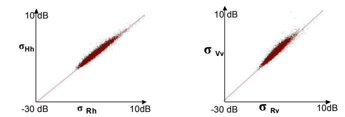
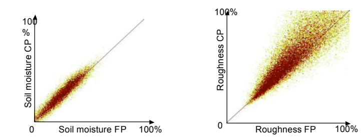


Figure 8: Comparison of soil moisture and surface estimates using the original Dubois et al algorithm (FP) and using the CP-based approach



Conclusions

The simulations presented here lead to the following major conclusion: we can use CP data, even in the presence of Faraday rotation and apply the Dubois et al algorithm to retrieve soil moisture estimates with a residual error of only 2%. The process starts with the discrimination of bare surfaces based on the conformity coefficient, which has the advantage of being FR independent over surfaces where the reflection symmetry hypothesis [8] is valid (this is the case for most natural surfaces, except in sloping terrain). Furthermore, we have shown that μ can be used as an discriminator of dominant scattering types (surface, double-bounce, volume). This new coefficient was also validated against the Freeman-Durden decomposition and the simple threshold test used in Dubois et al's paper to identify surface scattering.

Over bare surfaces, the Faraday rotation can be estimated and then corrected for over the full scene. Once the data is corrected, the co-pol measurements can be closely approximated by the CP measurements (as σ^o_{HV} is close to 0) over bare surfaces. The standard Dubois et al. algorithm, applied directly to the CP data provides soil moisture estimates very close to ones computed from the FP data. An RMS error of about 2% is found, indicating that the proposed procedure has very similar performances relative to the original algorithm. This provides a straightforward, easy to implement approach to soil moisture mapping from space, particularly for the SMAP mission [9]. The added value that CP mode measurements provide is in the phase information, that may be useful in estimating scattering from beneath forest canopies.

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